APPLICATION POTENTIAL OF BASALT FIBERS IN AERONAUTICS

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Abstract

Basalt fibers provide good mechanical properties as well as excellent thermal and chemical resistance. An evaluation of critical properties of off-the-shelf fibers is done with regard to application in high performance industries, particularly aerospace. In this field, low scatter of properties represents a basic requirement. Variations may be generated by the use of a natural raw material and further challenges from the production process. Basalt fiber spinning requires particular know-how that differs from glass and carbon fiber spinning. Fiber diameters were measured as an evaluation criterion for the process stability. Large differences in the diameter variation and therefore quality level were found. As the main property of interest, fiber mechanical strength was determined on single fiber and impregnated roving. An interrelationship could be found between fiber diameters and achieved mechanical strength.

1. Introduction

Recent development activities in the basalt fiber science and industry indicate ongoing improvements and a growing relevance of the material. A considerable amount of scientific work was published in the past few years [1]. Research clusters now support scientific exchange, market exploitation and the identification of possible applications. Both the increasing production capacity and a growing number of available semi-finished products may answer a rising demand. Moreover, some manufacturers are working on the development of more sophisticated high performance basalt fibers.

The properties of basalt fiber may expand the profile of currently used reinforcement fibers. Mechanical performance of basalt fibers is at an intermediate level between E-glass and carbon fiber [2]. Therefore application potential persists where carbon fiber is over-engineered and E-glass does not fulfill the requirements. In addition, the elongation to break between glass and carbon fiber indicates application potential where damage tolerant properties are required. A particular advantage of basalt fiber is seen in its thermal resistance even in oxygen atmosphere. Single fiber tensile tests at room temperature yield constant strength values for thermally conditioned fibers up to 400 °C [3]. Beyond that, crystallization processes are accounted for the decrease of strength [4]. Polymer matrix material represents the weak point of laminates at such elevated temperatures. However, an insulating and incombustible basalt fiber textile might serve as protective barrier during short term exposure to high temperature or fire. Furthermore, the high media resistance of the inert basalt fiber makes it insensitive during contact with corrosive media and for contact corrosion. The material price ranges slightly above E-glass and significantly below carbon fiber. Further price reductions are expected due to scale effects at larger production volumes. Environmental aspects are addressed by the low energy consumption during fiber production in comparison to carbon fiber and the use of an unlimited natural

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raw material sources. Possible advantages may also exist for recycling where the high thermal and media resistance could be used during matrix separation as well as the possibility to re-melt the fibers.

The aerospace industry, as the target field of application in this work, places high requirements on novel materials in terms of reliability, quality and properties. A key aspect during the examination of basalt fiber is the variation of properties within and between batches. Large scatter in properties requires increased safety factors and oversizing of structures, which reduce potential benefits of new material.

Possible origins of scatter of the final product are seen in the use of a natural raw material and the complex production process of basalt fiber. Raw material selection and refining are the first production steps. The chemical composition and homogeneity of the final product are affected by the choice of a basalt stone quarry, an appropriate quality control and individual modifications from the manufacturers. Crushed basalt stones are introduced to the melting furnace in a continuous or batch-wise mode. The heating is mostly carried out in two stages that differ in their precision of thermal control. The opaque character and low thermal conductivity of basalt reduce heat transfer via radiation and conduction. Convective transfer is rather ineffective in the viscous melt [5]. Infrared heating technologies that are used for effective through-volume heating of transparent glass melts are not applicable. Thermal and material inhomogeneity further confines the narrow processing window during spinning and may lead to fiber damage as well as variations in fiber shape and properties. Additional thermal control in the bushings is used by some manufacturers in order to meet this challenge. Directly after leaving the nozzle, the fiber is rapidly quenched and sized. A water spray enables rapid cooling to achieve a glassy material and prevent crystallization. Sizing is applied right after spinning as a protection of the abrasive fiber from damage during the subsequent refinement and processing stages. Small fiber diameters are produced by drawing from the winder which is coiling the fiber on the spinning cake at high speed. The number of nozzles is currently limited due to processing challenges so that the desired roving fineness is achieved by assembling of several roving. This process may induce mechanical damage and unequal catenary to the roving.

The process control is indirectly investigated in this work by analyzing fiber diameters as a quality criterion. The capability to produce small fibers indicates mastering of the process due to the fact that it happens at a more narrow process window. Available scatter in the diameters is seen as an indicator for inhomogeneity in the process. For the relation of fiber diameters it is expected that small diameters lead to higher mechanical strength values due to the size effect. Furthermore, a low scatter of diameters is estimated to have a positive impact on the homogeneity within the roving. Moreover, diameter variations along the fiber are assumed to induce weak points with a higher probability of failure.

2. Materials and methods

Basalt fiber roving of seven different manufacturers worldwide was sourced with the objective of getting an extensive overview of the current performance and quality level in the industry. For comparability, roving fineness was specified to 600 Tex and fiber diameters between 9 and 13 µm. Bobbins of three different production dates were sourced for the determination of batch to batch variations. Qualified aeronautical E-, R-, S2-glass and a Toray T800 carbon fiber are used as references.

The distribution of basalt fiber diameters was analyzed at polished sections of embedded roving. Curing under vacuum between prepreg plies enabled a pore-free impregnation by the resin bleed out. Optical microscopy was conducted on a Carl Zeiss AXIO Imager Z1. The pictures were analyzed with the ImageJ software to determine the diameter of the complete number of fibers in the roving.

Diameter variations along the fiber were measured by a VEGA II Tscan scanning electron microscope. Specimens were sputtered with Gold/Palladium to increase the conductivity of electrically insulating basalt. Measurements took place at an acceleration voltage of 25 kV with magnifications up to 15000 x.

Single fiber mechanical characterization was done on a Favimat+ tensile testing machine. The specimen is fixed in dedicated clamps. Before testing, the resonance frequency of the fiber specimen is

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measured by the optoelectronic unit after acoustic incitation. Linear fiber density and fiber diameter can be calculated from this value. The tensile test takes place under high-resolution force monitoring by a load cell up to 220 cN and precise moving of the clamps. Single fibers were loaded with a speed of 2 mm/min at a test length of 20 mm.
Composite related mechanical properties were determined by tensile testing of epoxy resin infiltrated roving strands. Appropriate gripping of the clamps is assured by Composite tabs which were glued on the specimen. Tests were done on a Zwick 1465 tensile testing machine with strain recording by a clip-on extensometer. Tensile testing of impregnated roving was performed at a free test length of 15 cm and a test speed of 5 mm/min.

3. Results and Discussion

Figure 1 depicts the narrow distribution of reference glass and carbon fiber diameters around a characteristic diameter on the lower end of the scale. In opposition to that, the results on basalt fibers indicate large differences among the manufacturers. Some show average diameters in the range of S2-glass and only slightly wider distribution. Others exhibit particularly large diameters and scatter.

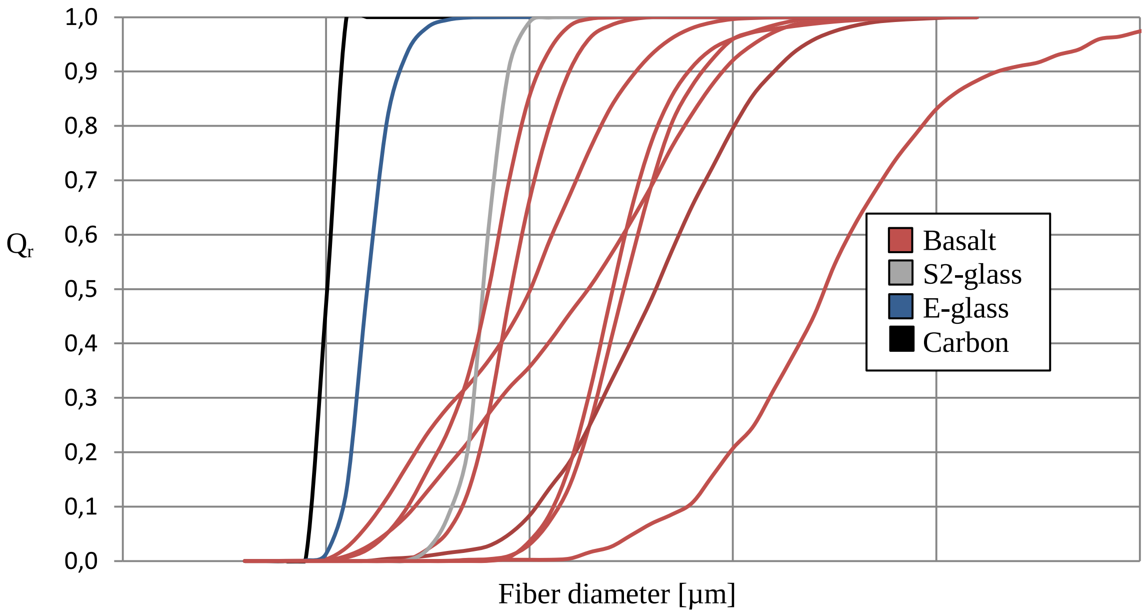

Figure 1: Fiber diameter distributions

Longitudinal fiber diameter deviation was determined by measuring 10 diameters along a fiber section of 30 cm via scanning electron microscopy. The standard deviation of the ten measurements is used as an indicator for the deviation and presented in Figure 2. The measurement error was determined to 0,29 % by calculating the standard deviation of 10 repeated measurements on the same spot of a fiber. With such high precision it is possible to detect the lengthwise diameter variations.

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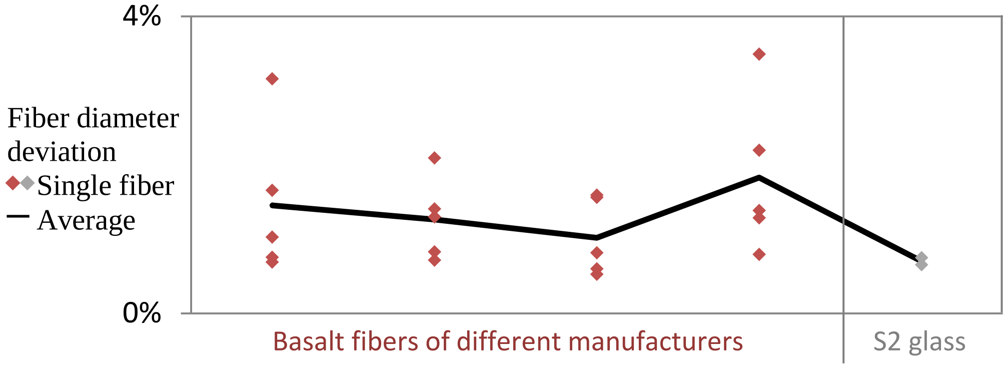

Figure 2: Scatter of longitudinal fiber diameter

The analysis reveals that the average and individual diameter fiber deviation is several times higher than the one for S2-glass. On the other hand, the results still remain in the magnitude of the reference at a low level.
The mechanical performance is used as an evaluation criterion for the impact and relevance of the deviations. Figure 3 plots the resulting mechanical values over the previously measured fiber diameters.

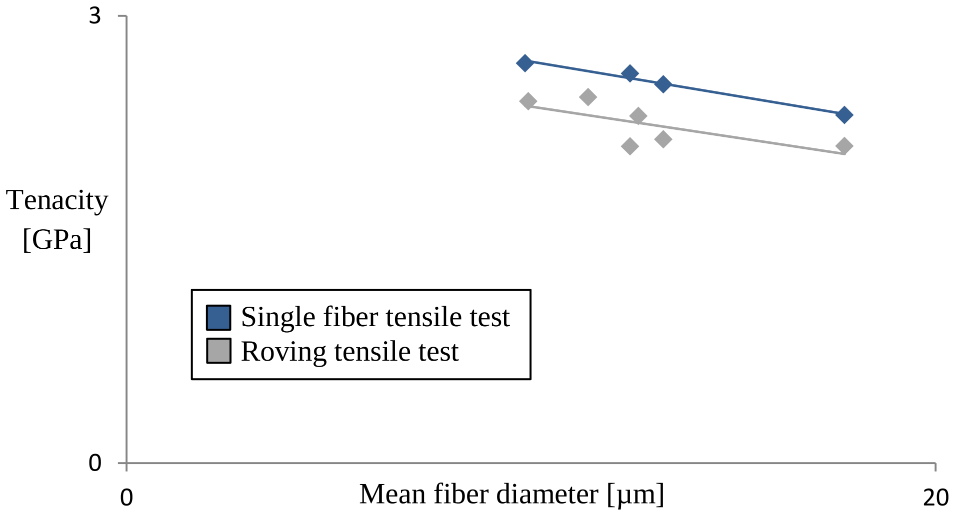

Figure 3: Interrelationship of fiber diameters and mechanical strength

An inverse proportionality of the mechanical strength and the fiber diameter is found during the analysis of both test types. Even a similar quantitative relationship is visible by the parallelism of the regression lines. The reduced strength values of the impregnated roving in comparison to the single fiber may be attributed to misalignment of fibers during specimen preparation.
No dependency could be found for the partly great scatter of fiber diameters on the mechanical values. A possible explanation was found in the single fiber modulus being independent of the fiber diameter. Like this, neighboring fibers of different diameters are subjected to similar stress and no weak points exist.

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4. Conclusions

Promising properties of basalt fiber are described by both the literature and manufacturers and form the motivation of this investigation. A literature research for reference values revealed different data for the respective property that may result from the different quality levels that currently exist. In some cases, comparability of given data was reduced due to uncertainty about the test parameters. For this reasons, a thorough investigation and generation of a database with consistent state of the art test methods is seen as a prerequisite for the use of basalt fiber in high performance applications.

The spinning process was identified as crucial source for deviations while the origin is not always clear. The suppliers were interviewed about their material selection and processing technologies to be able to explain deviations at a later date. In this study, the fiber diameter was used as an evaluation criterion for the material and thermal inhomogeneity in the process. Different results for the fiber diameter and its scatter were found for the fibers of the seven manufacturers in scope. Consequently the hypothesis was set up that the average diameter and its distribution represent different quality levels. An interrelationship between the fiber diameter and fiber dominated tensile strength values was detected. Higher strength is achieved at lower fiber diameters which simultaneously are more challenging to produce due to a narrow process window. This relation shows the importance of process control during basalt fiber spinning in order to achieve good and reliable properties.

It is concluded that the application of basalt fiber in high performance industries such as aerospace requires a test methodology to empirically detect and assess all relevant process parameters and their impact on the properties. For instance the small crystallites grown in the fiber during spinning may act as flaws. A potential measure is seen in the degree of crystallization in the fiber. Moreover, basalt fiber properties are connected to the chemical composition which may vary from raw material choice and process inhomogeneity.

Despite the described research tasks, a large potential for the use of basalt fibers is seen for high performance applications and aeronautics. This is derived from the combination of good mechanical properties and additional functional properties. The widely used carbon and glass fibers own a lead of several decades of basic research, development and continuous improvement. An increasing market demand for basalt fiber could help the manufacturers to catch up by incipient scale effects, continuous production in the equilibrium and the availability of financial means for research and development.

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